EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

*Ecological Engineering & Environmental Technology*, 2025, 26(6), 321–336
https://doi.org/10.12912/27197050/204394
ISSN 2719–7050, License CC-BY 4.0

Received: 2025.04.03
Accepted: 2025.04.21
Published: 2025.05.03

# Effects of season and aquifer on groundwater quality in the Mekong delta: A case study in Dong Thap province

Le Diem Kieu[1], Pham Quoc Nguyen[1*]

[1] Faculty of Agriculture, Natural Resources and Environment, Dong Thap University, Dong Thap, 81000, Vietnam
* Corresponding author's e-mail: pqnguyen@dthu.edu.vn

## ABSTRACT

Assessment of groundwater quality in Dong Thap province, Mekong Delta Vietnam, was based on monitoring data of 19 wells with 20 water quality parameters in March, June, August and December 2024 and combined with WPI, GWQI and correlation, PCA and CA analysis. The results showed that groundwater quality in the study area is quite good, with less variation between months and seasons of the year, but varies greatly according to the aquifer. The parameters exceeding QCVN and WHO only accounted for 25% (TH, TDS, $Cl^-$, $SO_4^{2-}$, Fe) originating mainly from soil and rock weathering; however, microbiological pollution (coliform and *E.coli*) was relatively high. The results of the WPI and GWQI analyses showed that the water quality in the dry season was relatively better than in the rainy season, and the water in deep aquifers was always better than in shallow aquifers. The water quality was mainly in the very good, good (WPI) and excellent, good (GWQI) groups. The results of the CA analysis showed that the average water quality of 19 monitored wells was divided into five groups. PCA analysis showed that seven PC groups explained 73.09% of the groundwater quality, and the sources of groundwater pollution in the locality were mainly natural, such as weathering, the interaction between water and rock, besides from artificial sources, such as waste from domestic activities, agricultural production and industrial wastewater.

**Keywords:** groundwater quality, microbial contamination, seasonal variation, groundwater aquifer, Dong Thap Province in Vietnam.

## INTRODUCTION

Groundwater is a very important freshwater source and well-protected under aquifers of soil and rock in the continent, so this is a significant source of freshwater (Ahmed and El-Rawy, 2024). Groundwater is essential in providing clean water for drinking and domestic use, agriculture, and industry and supporting and maintaining the ecosystem's health through preserving water resources, especially during droughts (Scanlon et al., 2023). This resource is impacted by human socio-economic exploitation, development activities, and natural factors such as climate change, salinity intrusion, flow, and geological composition (Ouhakki et al., 2025; Kieu and Nguyen, 2024). With the above impacts, groundwater has declined in quality and volume, creating challenges for this resource's prediction and sustainable management (You et al., 2020). Therefore, there have been many recent studies assessing groundwater quality. Assessment of groundwater quality based on standards and water quality indexes such as GWQI and WPI is widely applied due to their reliability and role in comprehensive and scientific information to serve better the effective management of this resource (Dash and Kalamdhad, 2021; Abbasnia et al., 2018; Hossain and Patra, 2020).

Dong Thap is one of 13 provinces and cities in the Mekong Delta Vietnam, with an area of about 338,385 ha, accounting for 8.17% of this area. Groundwater resources of Dong Thap province are distributed in two main areas: (1) In the area north of Nguyen Van Tiep canal, groundwater is mainly concentrated at a depth of 100–300 m; (2) The area south of the Nguyen Van Tiep Canal and south of the Tien River has abundant groundwater resources at different depths. In the context of local economic and social development in recent times, as well as the implementation of economic development goals of Dong Thap province towards a comprehensive, multi-sector, multi-sector economy and the rapid urbanization process in the province has and will powerfully change the structure of demand for exploitation and use of groundwater in both quality and quantity. Meanwhile, local groundwater resources have limited reserves, and the annual natural water supply is minimal (Tran et al., 2020). Therefore, assessing groundwater quality in Dong Thap province in 2024 by combining water quality indexes such as WQI, WPI, and statistical methods PCA, CA in the context of the Law on Water Resources and national standards on groundwater quality of the Ministry of Natural Resources and Environment of Vietnam (QCVN09/BTNMT) issued in 2023 is extremely necessary for the management of this resource in the future.

## RESEARCH METHOD

### Site description

Dong Thap, located at coordinates from 10°07' to 10°58' North latitude and from 105°12' to 105°56' East longitude, is a province in the Mekong Delta (Vietnam), with a total natural area of 338,228 hectares; its population in 2023 is 1,600.170 people (People's Committee of Dong Thap province, 2024). In addition to abundant surface water resources, the province also has abundant groundwater resources with a total potential exploitable reserve of about 2.8 million $^{m3}$/day, including seven principal aquifers: Holocene (qh), Upper Pleistocene (qp3), Middle-Upper Pleistocene (qp23), Lower Pleistocene (qp1), Middle Pliocene (n22), Lower Pliocene (n21) and Miocene (n13). The potentially exploitable reserve of 4 aquifers (qp23, n22, n21, n13) is 2,321,459 $m^3$/day. The Middle-Upper Pleistocene aquifer (qp2-3) has the most abundant groundwater reserve, estimated at 451,321 $m^3$/day, which is the main source of water supply for domestic activities in the region (Department of Natural Resources and Environment of Dong Thap province, 2013). However, the locality currently only grants licenses to exploit groundwater for public services such as domestic water supply, healthcare and education in the lower Pliocene (n21) and Miocene (n13) aquifers (People's Committee of Dong Thap province, 2019).

### Description of groundwater sampling and analysis

The study monitored 19 wells throughout the province to assess groundwater quality in Holocene (qh), Upper Pleistocene (qp3), Middle-Upper Pleistocene (qp2-3), Lower Pleistocene (qp1), Middle Pliocene (n22), Lower Pliocene (n21), and Miocene (n13). Groundwater samples were collected four times in 2024 (i.e., March, June, September and December). Groundwater samples were collected according to national standards in Vietnam regarding guidance on groundwater sampling (TCVN 6663-11:2011) (Ministry of Science and Technology, 2011). The wells' detailed coordinates, depths and water levels information are shown in Table 1.

Nineteen water samples (GW01-GW19) were collected from the Department of Natural Resources and Environment of Dong Thap Province in 2024. The water quality parameters were Temp., Turb., pH, TH, TDS, $Cl^-$, F, $SO_4^{2-}$, $N\text{-}NO_2^-$, $N\text{-}NO_3^-$, Fe, Mn, As, Pb, Cu, Zn, Cd, Hg, Coliform and *E. coli*. The sampling months were March, June, September, and December. Sampling, storage, and analysis methods were conducted according to the standard methods of QCVN09:2023/BTNMT (DONRE, 2025).

### Data analysis

#### *Groundwater quality index*

The groundwater quality index (GWQI) has been widely used in assessing the suitability of groundwater for drinking (Chakraborty et al., 2021; Das et al., 2021; Elemile et al., 2021). This method combines multiple data of physical, chemical and microbiological parameters of groundwater into a single value to assess groundwater quality, which will help to assess water quality more generally. In this study, the GWQI index of 19 wells was assessed based on 18 water quality parameters: pH, TDS, TH, $SO_4^{2-}$, $Cl^-$, F, $N\text{-}NO_2^-$, $N\text{-}NO_3^-$, Fe, Mn, As, Pb, Cu, Zn, Cd, Hg, Coliform and *E. coli*. GWQI is calculated using the formula (1) (Minh et al., 2019; Nadiri et al., 2022):

$$GWQI = \sum_{i=1}^{n} SI_i = \sum_{i=1}^{n} W_i \times q_i \quad (1)$$

In this case, $n$ is the number of groundwater quality variables, $SIi$ is the sub-index of each parameter, and $Wi$ is the relative weight of each

**Table 1.** Location, distribution and characteristics of 19 groundwater quality monitoring wells in Dong Thap province (DONRE, 2025)

| Monitoring well | Coordinates | | District/City | Well depth (m) | Groundwater level |
|---|---|---|---|---|---|
| | X | Y | | | |
| GW1 | 1180278 | 562072 | Tam Nong district | 292 | Lower Pliocene (n21) |
| GW2 | 1180275 | 562074 | Tam Nong district | 236 | Upper Pliocene (n22) |
| GW3 | 1180275 | 562073 | Tam Nong district | 168 | Middle - upper Pleistocene (qp23) |
| GW4 | 1180280 | 562075 | Tam Nong district | 24 | Holocen (qh ) |
| GW5 | 1180277 | 562073 | Tam Nong district | 137 | Middle - upper Pleistocene (qp23) |
| GW6 | 1157876 | 567717 | Cao Lanh city | 390 | Upper Miocene (n13) |
| GW7 | 1157874 | 567717 | Cao Lanh city | 260 | Upper Pliocene (n22) |
| GW8 | 1157872 | 567719 | Cao Lanh city | 41 | Holocen (qh ) |
| GW9 | 1157870 | 567722 | Cao Lanh city | 8 | Holocen (qh ) |
| GW10 | 1163904 | 592292 | Thap Muoi district | 323 | Lower Pliocene (n21) |
| GW11 | 1163902 | 592295 | Thap Muoi district | 247 | Upper Pliocene (n22) |
| GW12 | 1163901 | 592297 | Thap Muoi district | 191 | Lower Pleistocene (qp1) |
| GW13 | 1163906 | 592295 | Thap Muoi district | 85 | Upper Pleistocene (qp3 ) |
| GW14 | 1163902 | 592293 | Thap Muoi district | 37 | Holocen (qh ) |
| GW15 | 1140210 | 581414 | Sa Dec city | 390 | Upper Miocene (n13) |
| GW16 | 1140210 | 581414 | Sa Dec city | 205 | Lower Pleistocene (qp1) |
| GW17 | 1140206 | 581411 | Sa Dec city | 294 | Lower Pliocene (n21) |
| GW18 | 1140206 | 581411 | Sa Dec city | 120 | Middle - upper Pleistocene (qp23) |
| GW19 | 1180272 | 562073 | Tam Nong district | 324 | Lower Pliocene (n21) |

parameter. *Wi* represents the role of the parameter in the entire monitoring data and is calculated according to formula (2) (Tham et al., 2022):

$$W_i = \frac{\frac{1}{\sum_{i=1}^{n} \frac{1}{Si}}}{Si} \quad (2)$$

where: *Si* – limit value of each parameter specified in QCVN09-MT:2023/BTNMT.

Parameter *qi* is the quality assessment scale and is determined according to formula (3) (Nadiri et al., 2022):

$$q_i = \frac{C_i}{S_i} \times 100 \quad (3)$$

where: $C_i$ is the concentration of each environmental parameter, and $S_i$ is the corresponding standard limit according to QCVN 09-MT:2023/BTNMT.

Water quality classification according to the GWQI index is divided into five levels: (1) “excellent” when GWQI ≤ 25, (2) “good” when GWQI ranges from 26–50, (3) “poor” when GWQI ranges from 51–75, (4) “very poor” when GWQI ranges from 76–100, and (5) “unsuitable for drinking” when GWQI is more significant than 100 (Elemile et al., 2021).

## Water pollution index

The water pollution index (WPI) is also widely used to assess the level of groundwater pollution (Biswas et al., 2023). In this study, the WPI was calculated based on 18 water quality parameters (i.e., pH, TH, TDS, F, N-$NO_2^-$, N-$NO_3^-$, $SO_4^{2-}$, $Cl^-$, Fe, Mn, As, Pb, Cu, Zn, Cd, Hg, Coliform and *E. coli*) monitored in 19 wells with four sampling periods (March, June, September and December) in 2024. The WPI was calculated using the formula (4):

$$WPI = \frac{1}{n} \sum_{i=1}^{n} PL_i \quad (4)$$

where: *PLi* is the pollutant load of water quality parameters calculated by formula (5) (except pH).

Formula (6) calculates *PL* of *pH* when the *pH* value is less than 7, and formula (7) if the pH is greater than 7.

$$PL_i = 1 + \left(\frac{C_i - S_i}{S_i}\right) \quad (5)$$

$$PL_{pH} = 1 + \left(\frac{C_i - 7}{S_{i1} - 7}\right) \quad (6)$$

$$PL_{pH} = 1 + \left(\frac{C_i - 7}{S_{i2} - 7}\right) \quad (7)$$

where: $C_i$ is the parameter's observed concentration, and *Si* is the maximum limit value according to QCVN09:2023/BTNMT. $S_{i1}$ and $S_{i2}$ are the minimum and maximum limit values of pH.

Groundwater quality according to WPI is divided into four levels: (1) excellent when WPI < 0.5, (2) good when 0.5 ≤ WPI < 0.75, (3) moderately polluted when 0.75 ≤ WPI < 1, and (4) highly polluted and unsuitable for human use when WPI ≥ 1 (Hossain and Patra, 2020).

### *Pearson correlation analysis*

Pearson correlation analysis is a method to estimate the degree of association between multiple related variables in the study. Pearson correlation is calculated according to formula (8):

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X}) \times (Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2} \times \sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \quad (8)$$

where: $r$ – Pearson correlation coefficient r between parameter $X$ and $Y$; $n$ – number of observations; $Xi$ – value of $X$ for the $i$ observation; $Yi$ – value of $Y$ for the $i$ observation.

In this study, the correlation between 20 water quality parameters is evaluated, which are Temp., Turb., pH, TH, TDS, $Cl^-$, $SO_4^{2-}$, F, N-$NO_2^-$, N-$NO_3^-$, Fe, Mn, As, Pb, Cu, Zn, Cd, Hg, Coliform and *E.coli*. The r value will range from -1 to 1; r with the (-) sign represents a negative correlation, and r without the sign is understood as (+) representing a positive correlation between the parameters. The correlation is strong when the value |r| > 0.5, medium correlation when |r| has a value ranging from 0.3–0.5; and weak correlation when the coefficient |r| < 3 (Prathumratana et al., 2008; Heale and Twycross, 2015).

Principal component analysis (PCA) was applied to identify the main parameters affecting the study area's water quality. The eigenvalue coefficient of each PC was used to assess the contribution to surface water quality, which will increase with the value of this coefficient. The correlation between PCs and water quality parameters expresses a coefficient of 1 to -1 (Feher et al., 2016). CA was used in this study to group the evaluated wells based on their similarity in water quality. Ward's method and Euclidean range were used to measure similarity between wells (Zhou et al., 2007). CA and PCA were performed using SPSS 22 software.

## Multivariate analysis

The water quality data in this study were evaluated and analyzed using one-way ANOVA with Duncan's test ($p < 0.05$) to compare water quality, GWQI, WPI values of sampling wells, water aquifers, survey months and between groups of wells grouped after CA analysis. Pearson correlation analysis was used to evaluate the relationship between water quality parameters. PCA was used to identify sources of groundwater pollution based on water quality variables. CA was applied to group monitoring wells with similar groundwater quality. Statistical analyses were performed using SPSS 22 software. The study flow is shown in the Figure 1.

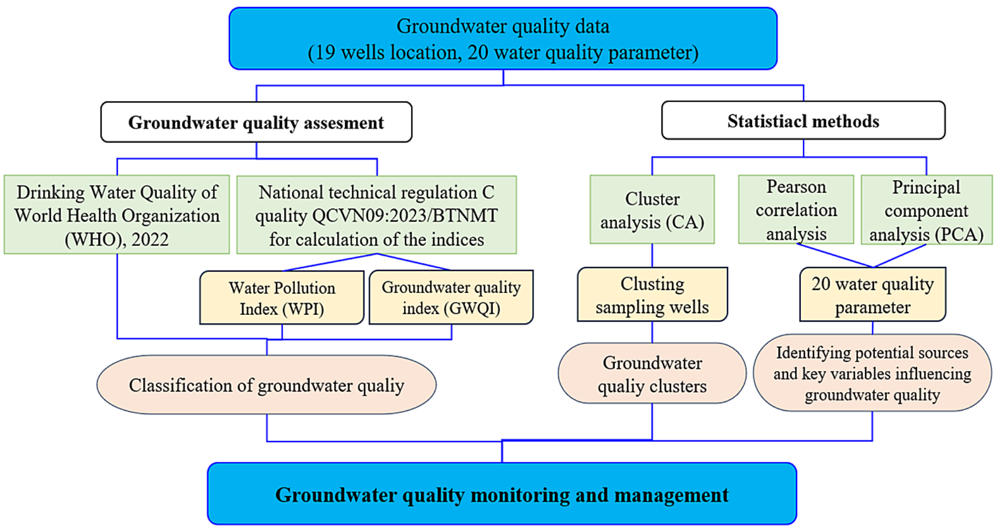


**Figure 1.** Flow of study

## RESULTS AND DISCUSSION

### Characteristics of groundwater in Dong Thap Province

The groundwater temperature in 19 monitored wells varied according to the monitoring months, in which the water temperature in March and June was higher than that in September and December ($p < 0.05$, Table 2). The groundwater temperature in the area is relatively stable, with the water temperature amplitude only fluctuating from 28.93±1.3 °C (December) to 30.68±0.97 °C (March) because the air temperature of the area also has little seasonal fluctuations, and the terrain of the area is flat. Temperature is a physical parameter that affects the ability to exploit and use, such as controlling palatability and viscosity, and also affects water's solubility, odor, and chemical reaction (Omer, 2019).

The average pH value of groundwater fluctuated from 7.24±0.59 (December) to 7.7±0.56 (March), with no difference between months in 2024 ($p > 0.05$; Table 2). However, the pH of groundwater fluctuated and increased with depth. The pH of water in the Pliocene aquifer above n21 and the Miocene aquifer above n13 was alkaline ($p < 0.05$). The pH of groundwater in the monitored wells was within the limits of QCVN09:2023/BTNMT, but the pH of water in the Miocene aquifer above n13 was 8.22±0.3, which was higher than the WHO regulations (7.0–8.0) (Table 3). The pH of groundwater is affected by dissolved salts such as carbonates, bicarbonates, silicates, fluorides, and other salts in dissociated form. High pH has demonstrated that groundwater has high sodium concentration and low free acidity (Kushwah et al., 2012). The average pH of groundwater in Dong Thap province in 2024 is similar to that of An Giang, Dong Thap, Kien Giang, and Hau Giang provinces in 2019, with groundwater pH values ranging from 6.88 to 7.25, 6.98–7.76, 6.54–7.36 and 6.84–7.32, respectively (Giao and Nhien, 2023), and the middle-upper Pleistocene groundwater (qp 2–3) in Hau Giang province in May and October 2022 also has pH 6.75–7.58 (Kieu and Nguyen, 2024).

Similar to the pH value, the hardness value of groundwater also did not fluctuate according to the months of the year with 385.71±398.78 mg/L (August) to 458.63±398.72 mg/L (June) ($p > 0.05$; Table 2). The average hardness fluctuated

**Table 2.** Changes in groundwater quality over time of year

| Pac. | Unit | March | June | August | December | Sig. | QCVN09:2023 | WHO 2022 |
|---|---|---|---|---|---|---|---|---|
| Temp. | C | 30.68±0.97$^{a}$ | 30.35±1$^{a}$ | 29.4±0.59$^{b}$ | 28.93±1.3$^{b}$ | 0.000 | | |
| Turb. | NTU | 21.18±41.78 | 22.12±46.78 | 18.28±19.63 | 10.2±10.04 | 0.681 | | |
| pH | | 7.7±0.56 | 7.25±0.85 | 7.42±0.75 | 7.24±0.59 | 0.151 | 5.8–8.5 | 7.0–8.0 |
| TH | mg/L | 419.42±363.87 | 458.63±398.72 | 385.71±398.78 | 444.71±358.01 | 0.939 | 500 | 500 |
| TDS | mg/L | 837.32±394.7 | 1100.37±986.69 | 1217.21±1066.98 | 1519.89±1509.13 | 0.269 | 1500 | |
| $Cl^-$ | mg/L | 634.54±732.09 | 468.74±518.46 | 418.89±481.87 | 432.54±400.65 | 0.599 | 250 | 250 |
| F | mg/L | 0.7±0.$^{2}$a | 0.5±0.1$^{6}$b | 0.63±0.13$^{ab}$ | 0.62±0.31$^{ab}$ | 0.038 | 1 | 1.5 |
| $SO_4^{2-}$ | mg/L | 190.08±283.83 | 169.72±259.7 | 120.01±143.13 | 103.56±153.42 | 0.581 | 400 | 250 |
| $N\text{-}NO_2^-$ | mg/L | 0.09±0.25 | 0.15±0.24 | 0.1±0.14 | 0.03±0.07 | 0.328 | 1 | 3 |
| $N\text{-}NO_3^-$ | mg/L | 0.16±0.26 | 0.29±0.27 | 0.22±0.19 | 0.15±0.11 | 0.163 | 15 | 50 |
| Mn | mg/L | *0.2±0.14* | 1.65±3.45 | 1.02±1.46 | 0.59±0.71 | 0.118 | 0.5 | 0.08 |
| Fe | mg/L | 6.93±11.51 | *0.31±0.57* | 7.54±12.67 | *4.28±5.52* | 0.063 | 5 | 0.3 |
| As | mg/L | 0.001±0.003 | 0.001±0.004 | 0.001±0.001 | 0.001±0.001 | 0.774 | 0.05 | 0.01 |
| Pb | mg/L | 0±0 | 0.009±0.025 | 0±0 | 0.001±0.001 | 0.074 | 0.01 | 0.01 |
| Cu | mg/L | 0±0 | 0.003±0.007 | 0±0 | 0±0 | 0.071 | 1 | 2 |
| Zn | mg/L | 0±0$^{b}$ | 0.018±0.029$^{a}$ | 0.015±0.022$^{a}$ | 0.005±0.018$^{ab}$ | 0.021 | 3 | |
| Cd | mg/L | 0.001±0$^{b}$ | 0.002±0.004$^{a}$ | 0.001±0.001$^{b}$ | 0.001±0.001$^{b}$ | 0.037 | 0.005 | 0.003 |
| Hg | mg/L | 0±0 | 0±0 | 0±0 | 0±0 | 0.258 | 0.001 | 0.006 |
| Coliform | MPN/100 ml | 342.53±358.52 | 1242.58±2539.4 | 249.32±234.58 | 319.84±365.18 | 0.067 | 3 | |
| *E.coli* | MPN/100 ml | 37.42±31.19 | 247.53±544.11 | 23.63±20.62 | 70±82.35 | 0.053 | 0 | 0 |

between aquifers; the highest was in the Pleistocene qp23 aquifer with 877.71±385.97 mg/L, and the lowest was in the upper Pliocene aquifer (n21) with 136.03±88.39 mg/L ($p < 0.05$). The hardness of water in the Pleistocene qp1 and Pleistocene qp23 aquifers exceeded 1.2 to 1.8 times the QCVN and WHO (500 mg/L) (Table 3). Groundwater hardness in An Giang, Soc Trang, and Hau Giang provinces has also exceeded the standard (Giao and Nhien, 2023; Kieu and Nguyen, 2024). Groundwater hardness is mainly due to the influence of cations such as calcium, magnesium, and anions such as carbonate, chloride, bicarbonate, and sulfate originating from water-rock interactions and human activities (WHO, 2017). High groundwater hardness can reduce water quality, increase water treatment costs, and cause metal dissolution affecting pipes and metal objects (Kumar et al., 2024). In addition, high hardness also affects human health such as causing heart disease and kidney stones (Ram et al., 2021), microcephaly, prenatal death, leukemia, and cardiovascular problems (Kumar et al., 2024). The TDS concentration of groundwater did not differ between months but varied by aquifer. The TDS concentration of groundwater in the study area ranged from 411.75±151.98 mg/L (Upper Pliocene aquifer n21) to 1730.88±1494.02 mg/L (Pleistocene aquifer qp1). The average TDS concentration of groundwater in December (1519.89±1509.13 mg/L) and Pleistocene aquifer qp23, Pleistocene qp1 began to be higher than QCVN09:2023/BTNMT (Table 3). TDS in water includes inorganic salts, including sodium, magnesium, calcium, potassium, sulfate, chloride, bicarbonate, and only a small amount of dissolved organic matter (WHO, 2017). Groundwater often has a higher TDS concentration than surface water due to long-term contact with a large mineral surface area (WHO, 2022).

The average $Cl^-$ concentration of groundwater did not differ between months of the year and was higher than the regulations of QCVN and WHO from 1.67 (August) to 2.54 times (March) (Table 2). The $Cl^-$ concentration of water in shallow aquifers was higher than in deep aquifers. It was mostly higher from 1.04 (Pliocene above n22) to 3.82 times (Pleistocene qp1) compared to QCVN and WHO, only water in the upper Pliocene aquifer

**Table 3.** Groundwater quality changes by aquifer

| Pac. | Unit | Holocen qh | Pleistocen qp3 | Pleistocen qp23 | Pleistocen qp1 | Pliocen n22 | Pliocen n21 | Miocen n13 | Sig. |
|---|---|---|---|---|---|---|---|---|---|
| Temp. | °C | 29.89±1.08 | 29.45±0.41 | 29.49±0.79 | 30±1.1 | 30.21±1.69 | 29.86±0.85 | 29.74±2.07 | 0.851 |
| Turb. | NTU | $23.38±24.39^{b}$ | $24.38±20.9^{b}$ | $4.67±6.02^{b}$ | $54.68±84.38^{a}$ | $17.11±11.76^{b}$ | $8.75±12.2^{b}$ | $6.7±12.51^{b}$ | 0.017 |
| pH | | $7.01±0.6^{cd}$ | $6.74±0.77^{d}$ | $7.12±0.66^{cd}$ | $7.4±0.89^{bc}$ | $7.29±0.48^{bcd}$ | $7.86±0.45^{ab}$ | $8.22±0.3^{a}$ | 0.000 |
| TH | mg/L | $462.71±341.64^{bc}$ | $364.33±86.59^{bcd}$ | $877.71±385.97^{a}$ | $601.69±497.65^{ab}$ | $316.48±207.77^{bcd}$ | $136.03±88.39^{d}$ | $285.03±225.13^{cd}$ | 0.000 |
| TDS | mg/L | $1343.69±818.68^{ab}$ | $871±301.78^{ab}$ | $1690.08±979.76^{a}$ | $1730.88±1494.02^{a}$ | $1058.83±1550.93^{ab}$ | $411.75±151.98^{b}$ | $1302±998.01^{ab}$ | 0.023 |
| $Cl^-$ | mg/L | $571.07±462.8^{ab}$ | $316.24±219.1^{b}$ | $957.41±620.9^{a}$ | $954.98±833.65^{a}$ | $259.04±253.81^{b}$ | $102.27±85.85^{b}$ | $357.97±391.98^{b}$ | 0.000 |
| F | mg/L | 0.6±0.24 | 0.62±0.27 | 0.63±0.2 | 0.59±0.26 | 0.58±0.18 | 0.63±0.26 | 0.63±0.18 | 0.998 |
| $SO_4^{2-}$ | mg/L | $210.64±310.89^{ab}$ | $103.3±47.44^{b}$ | $208.55±165.15^{ab}$ | $319.72±371.79^{a}$ | $90.85±126.98^{b}$ | $56.04±31.99^{b}$ | $31.66±12.69^{b}$ | 0.030 |
| $N\text{-}NO_2^-$ | mg/L | 0.04±0.08 | 0.02±0.01 | 0.16±0.33 | 0.12±0.18 | 0.05±0.12 | 0.1±0.13 | 0.2±0.28 | 0.361 |
| $N\text{-}NO_3^-$ | mg/L | 0.12±0.14 | 0.17±0.09 | 0.2±0.29 | 0.23±0.18 | 0.22±0.27 | 0.17±0.19 | 0.42±0.23 | 0.106 |
| Mn | mg/L | 1.09±1.69 | 1.18±0.63 | 1.16±1.2 | 2.26±5.18 | 0.39±0.62 | 0.3±0.47 | 0.25±0.28 | 0.276 |
| Fe | mg/L | $4.88±6.13^{bc}$ | $16.43±21.35^{a}$ | $7.08±9.91^{bc}$ | $10.77±16.5^{ab}$ | $2.67±3.34^{bc}$ | $0.88±1.58^{c}$ | $0.13±0.14^{c}$ | 0.010 |
| As | mg/L | 0.002±0.003 | 0.002±0.003 | 0±0 | 0.002±0.007 | 0.001±0.001 | 0±0.001 | 0±0 | 0.348 |
| Pb | mg/L | 0.001±0.001 | 0.003±0.004 | 0.009±0.031 | 0.001±0.001 | 0.001±0.003 | 0.002±0.008 | 0±0 | 0.669 |
| Cu | mg/L | 0±0 | 0±0 | 0.001±0.003 | 0±0 | 0.003±0.009 | 0.001±0.003 | 0±0 | 0.694 |
| Zn | mg/L | $0.011±0.018^{b}$ | $0.053±0.038^{a}$ | $0.005±0.008^{b}$ | $0.005±0.008^{b}$ | $0.013±0.031^{b}$ | $0.001±0.003^{b}$ | $0.008±0.021^{b}$ | 0.001 |
| Cd | mg/L | 0.001±0.001 | 0.001±0.001 | 0.002±0.005 | 0.001±0.001 | 0.001±0.001 | 0.001±0.002 | 0±0 | 0.803 |
| Hg | mg/L | 0±0 | 0±0 | 0±0 | 0±0 | 0±0 | 0±0 | 0±0 | 0.275 |
| Coliform | MPN /100mL | 470.19±367.61 | 191.5±204.03 | 1165.58±3109.04 | 435.38±413.27 | 365.17±645.93 | 643.19±909.39 | 62.38±80.51 | 0.651 |
| *E.coli* | MPN/ 100mL | 58.19±56.65 | 19.25±18.08 | 83.33±126.29 | 74.38±76.15 | 42±63.42 | 247.31±592.7 | 16.13±31.22 | 0.408 |

(n21) with a $Cl^-$ concentration of 102.27±85.85 mg/L meets the regulations of these two standards (Table 3). The $Cl^-$ concentration in groundwater in Dong Thap province was lower than that in Hau Giang province, with $Cl^-$ concentration ranging from 731.40 ± 806.74 to 1,212.34 ± 133.27 mg/L (Kieu and Nguyen, 2024). The main source of $Cl^-$ in groundwater is the weathering process of rocks and soils (Al-Ridah et al., 2021), and can originate from wastewater containing detergents and soil leaching (Ramesh and Thirumangai, 2014; Sunitha and Reddy, 2022; Mairizki and Cahyaningsih, 2016). Using groundwater with high $Cl^-$ concentration will cause laxative effects (Sunitha and Reddy, 2019) and increase blood pressure, significantly increasing the risk of stroke and kidney failure in patients with heart and kidney disease (Ramesh and Thirumangai, 2014). High $Cl^-$ concentration in irrigation water can also harm crops (Sunitha and Reddy, 2022).

The Fluorine (F) concentration of groundwater varies between months of the year; the highest is in March (0.7±0.2 mg/L), and the lowest is in June (0.5±0.16 mg/L) (Table 2). The F concentration did not change by aquifer, and both meet QCVN (1 mg/L) and WHO (1.5 mg/L) standards, which were safe for humans when used directly for different purposes (Table 3). According to Adimalla and Qian (2019), the absorption of small amounts of fluoride is beneficial to human health because F levels below 0.5 mg/L can support growth and strengthen bones, below 0.6 mg/L can cause tooth decay, levels of 0.8–1.0 mg/L reduce tooth decay and promote enamel production in children under 8 years old (Sunitha and Reddy, 2018). However, the F concentration is higher than 1.2 mg/L, it causes dental fluorosis in children, and higher than 4.0 mg/L promotes dental and skeletal fluorosis (Adimalla and Qian, 2019). F in groundwater is mainly from fluorides such as fluorspar or calcium fluoride ($CaF_2$), apatite or phosphate rock ($Ca_3F(PO_4)_3$), and cryolite ($Na_3AlF_6$) (Sunitha et al., 2012).

The average $SO_4^{2-}$ concentration of groundwater does not differ between months of the year ($p > 0.05$; Table 2) and has a decreasing trend with the depth of the water aquifers ($p < 0.05$). The $SO_4^{2-}$ concentration of groundwater all met QCVN (400 mg/L) and WHO (250 mg/L), except for water in the Pleistocene aquifer (qp1) with an average $SO_4^{2-}$ concentration of 319.72±371.79 mg/L, 1.28 times higher than the WHO regulation (Table 3). The average $SO_4^{2-}$ concentration of groundwater in Dong Thap province in 2024 was higher than that of Can Tho city (22.1–67.4 mg/L) (Giao et al., 2022a) and Bac Lieu province (36.9–137.6 mg/L), but lower than that of Soc Trang province (0.02–3239 mg/L) (Tran et al., 2020; Giao et al., 2022b). $SO_4^{2-}$ in groundwater is mainly derived from natural sources such as weathering of sulfate minerals and gypsum-containing sedimentary rocks (Das et al., 2021), rainwater dissolving sulfur-containing gases and seeping into groundwater (causing increased $SO_4^{2-}$ concentration in the rainy season and at the shallow aquifer) (Giao et al., 2022b), as well as being added from human activities such as fertilizer use, domestic wastewater containing chemicals such as detergents (Ramesh and Thirumangai, 2014; Farooqi et al., 2007; Paternoster et al., 2021). High sulfate concentration in water makes water taste bitter and causes health effects such as difficulty breathing, dehydration, gastrointestinal irritation, and diarrhea (Nguyen et al., 2021; Ramesh and Thirumangai, 2014). For water management and supply, sulfate will cause scale accumulation in water pipes (Sharma and Kumar, 2020).

The average $N\text{-}NO_2^-$ and $N\text{-}NO_3^-$ concentrations in groundwater in the study area were very low, and all met QCVN and WHO standards for human health safety. The average $N\text{-}NO_2^-$ and $N\text{-}NO_3^-$ concentrations of the surveyed wells also did not change according to the months of the year and the water aquifers (Table 2, Table 3). The $N\text{-}NO_2^-$ concentration in this study was similar to that in Hau Giang province, with the $N\text{-}NO_2^-$ concentration of the Pleistocene qp2-3 aquifer fluctuating from 0–0.06 mg/L and also did not change between sampling times (Kieu and Nguyen, 2024). The results showed that agricultural activities and human waste have not affected the $N\text{-}NO_2^-$ and $N\text{-}NO_3^-$ concentrations in groundwater in the locality.

The average Mn concentration of groundwater ranged from 0.2±0.14 mg/L (March) to 1.65±3.45 mg/L (June). The average Mn concentration of groundwater in August and June was higher than QCVN09:2023/BTNMT and higher than in March and December, but not statistically different ($p > 0.05$). The Mn concentration of groundwater in all months and aquifers was higher than the WHO standard (0.08 mg/L). The Mn concentration of groundwater in Dong Thap province in 2024 did not fluctuate much compared to 2019 (0.01–4.82 mg/L) but was higher than the Mn concentration in groundwater in An Giang and Kien Giang provinces 0–1.69 mg/L and 0–0.43 mg/L (Giao and

Nhien, 2022). The Mn concentration in groundwater in the study area can cause poisoning and adversely affect human health when used for a long time (Ye et al., 2017; Kubier et al., 2020). Mn in groundwater mainly originates from leaching Mn-containing rocks and industrial wastewater (Ghosh et al., 2020).

The average iron concentration did not differ between months of the year; however, the Fe concentration in March and August, in the deep groundwater was higher than the regulation of QCVN (5 mg/L), and all months had a higher concentration of this metal than the regulation of WHO (0.3 mg/L). The Fe concentration tended to decrease with depth of aquifer ($p < 0.05$) and ranged from 0.13±0.14 mg/L (upper Miocene n13) to 16.43±21.35 mg/L (Pleistocene qp3). Only the water in the Pleistocene aquifer (qp3, qp2-3), Pleistocene (qp1) did not meet QCVN, but when compared with the regulation of WHO, only the upper Miocene (n13) met this standard (Table 2, Table 3). The proportion of groundwater samples meeting QCVN standards for Fe concentration was 75%, while the proportion meeting WHO standards was only 38.2% of the total groundwater samples evaluated. The Fe concentration in groundwater in this study was higher than the Fe concentration of water in the Pleistocene qp 2–3 aquifer in Hau Giang (0–5.21 mg/L) (Kieu and Nguyen, 2024). Using water with high Fe concentration can cause reduced lung function and reproduction (Mairizki and Cahyaningsih, 2016; Xia et al., 2022). High Fe concentration in water also causes rust and blockage of pipes in water supply and distribution systems (Xia et al., 2022).

Groundwater in the study area had a relatively low and stable concentration of heavy metals. The concentration of these metals had almost no change according to season and aquifer, except for Zn concentration in June and August, which was higher than in March; Cd concentration in June was also higher than in other months, Zn concentration in Pleistocene qp3 aquifer was also higher than other aquifers ($p < 0.05$). The samples without detected heavy metals As, Pb, Cu, Zn, Cd, and Hg are 60.5, 78.9, 96.1, 69.7, 22.4, and 50.0%, respectively. As, Cu and Zn had a percentage of samples meeting QCVN of 100%, Pb and Cd were 97.4%, and Hg was 50% of samples meeting QCVN. Compared with WHO regulations, only Cu concentration has 100% of samples meeting the standard. For other metals such as As, Pb, Hg, and Cd, the proportion of samples meeting the standards was 98.7, 97.4, 96.1 and 93.4%, respectively. The average concentrations of heavy metals by season and by aquifer all met QCVN and WHO standards (Table 4). Thus, the groundwater in the study area had heavy metal concentration at safe levels for humans when used for different purposes.

The average Coliform and *E.coli* densities in June were higher than in other months, but there were no statistical difference ($p > 0.05$). Coliform and E.coli density fluctuated wildly between aquifers, but there were no statistical difference. Coliform and E.coli density were much higher than the regulations of QCVN. Coliform and E.coli density fluctuated wildly between monitoring wells, higher than the groundwater assessment results in 2019 in the An Giang, Dong Thap, and Kien Giang provinces (Giao and Nhien, 2022). Coliform and *E.coli* pollution in groundwater is mainly from human and animal waste, domestic wastewater, and agricultural fertilizers contaminated with feces (WHO, 2022; Ouhakki et al., 2025). High concentrations of Coliform and *E. coli* in groundwater have shown that sanitary waste management in the study area has not achieved good results. Solutions are needed to handle microbiological pollution in groundwater exploitation to provide domestic water for people. Because coliform bacteria

**Table 4.** Heavy metal pollution status in soil and water

| Pac. | Rate of undetected samples (%) | Rate of samples meeting Vietnamese standards (%) | Rate of samples meeting WHO standards (%) |
|---|---|---|---|
| As | 60.5 | 100 | 98.7 |
| Fe | 0 | 75.0 | 38.2 |
| Pb | 78.9 | 97.4 | 97.4 |
| Cu | 96.1 | 100 | 100 |
| Zn | 69.7 | 100 | - |
| Cd | 22.4 | 97.4 | 93.4 |
| Hg | 50.0 | 50 | 96.1 |

and Escherichia coli are present in organs other than the digestive system, they can cause serious diseases when they appear in different parts of the human body, such as urinary tract infections, sepsis, and meningitis (WHO, 2022).

## Correlation of water quality parameters

The correlation analysis results of 20 groundwater quality parameters of 19 wells monitored in 2024 recorded a specific correlation of water quality parameters, shown in the Table 5. According to the correlation assessment levels of (Prathumratana, 2008; Heale and Twycross, 2015), pH was correlated with many water quality parameters, mainly with moderate negative correlations with turbidity, Chlorine, Mn, Fe, and Zn; quite strongly negative correlation with $SO_4^{2-}$ and TS, on the contrary, pH is positively correlated at an average level with N-$NO_3^-$ concentration. $Cl^-$ and $SO_4^{2-}$ were strong anions that increase the acidity of water, and the weathering and dissolution of Mn, Fe, and Zn compounds occured under low pH conditions. Hardness was positively correlated with turbidity, Chlorine, $SO_4^{2-}$, Mn. TS and turbidity positively correlated with Chlorine, Mn, As, and Fe. Positive correlations between metals such as Cd-Pb (very strong with correlation coefficient 0.953, $p < 0.01$), at an average level between Cu and Zn. In addition, there was also a moderate positive correlation between N-$NO_3^-$ and N-$NO_2^-$, coliform with E. coli, N-$NO_2^-$ and coliform. Positive correlations between non-metals and metals included $Cl^-$ with $SO_4^{2-}$ at a strong correlation level, $Cl^-$ with Mn, Fe (average), $SO_4^{2-}$ and Fe.

## Water quality index of groundwater in Dong Thap province

### *WPI index*

The average groundwater WPI at the sampling points did not change seasonally. The average WPI in the dry season was 0.53±0.34, ranging from 0.25±0.06 (Pliocene n22 GW6) to 1.25±0.47 (GW12, Holocene qp aquifer) and in the rainy season it was 0.64±0.06, ranging from 0.22±0.05 (GW1, Miocene n13) to 2.28±0.99 (GW12, Holocene qh aquifer). Except for GW4, the water quality in the rainy season was better than in the dry season ($p < 0.05$). There was different in WPI between monitoring points in the rainy and dry seasons ($p < 0.05$). According to

**Table 5.** Correlation of groundwater quality parameters in Dong Thap province

| Parameter | Temp. | Turb. | pH | TH | TDS | Cl- | F | $SO_4^{2-}$ | N-$NO_2^-$ | N-$NO_3^-$ | Mn | Fe | As | Pb | Cu | Zn | Cd | Hg | Coliform |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temp. | 1 | | | | | | | | | | | | | | | | | | |
| Turb. | 0.19 | 1 | | | | | | | | | | | | | | | | | |
| pH | 0.076 | -.280* | 1 | | | | | | | | | | | | | | | | |
| TH | 0.041 | 0.176 | **-0.569**** | 1 | | | | | | | | | | | | | | | |
| TDS | 0.025 | 0.136 | -0.270* | **0.531**** | 1 | | | | | | | | | | | | | | |
| $Cl^-$ | 0.124 | 0.341** | -0.441** | **0.838**** | **0.533**** | 1 | | | | | | | | | | | | | |
| F | -0.087 | 0.013 | -0.075 | 0.065 | 0.030 | 0.033 | 1 | | | | | | | | | | | | |
| $SO_4^{2-}$ | 0.196 | 0.451** | **-0.548**** | **0.708**** | .420** | **0.799**** | 0.154 | 1 | | | | | | | | | | | |
| N-$NO_2^-$ | -0.106 | -0.135 | 0.270* | 0.078 | 0.024 | 0.227* | -0.287* | -0.053 | 1 | | | | | | | | | | |
| N-$NO_3^-$ | 0.159 | -0.052 | 0.318** | -0.179 | -0.087 | 0.037 | -0.191 | -0.124 | 0.496** | 1 | | | | | | | | | |
| Mn | 0.085 | **0.551**** | -0.462** | 0.422** | 0.302** | 0.446** | 0.019 | **0.579**** | -0.084 | -0.151 | 1 | | | | | | | | |
| Fe | 0.013 | 0.374** | -0.323** | 0.420** | 0.164 | 0.395** | 0.154 | 0.307** | -0.208 | -0.185 | 0.044 | 1 | | | | | | | |
| As | 0.15 | **0.668**** | -0.199 | 0.037 | 0.141 | 0.190 | 0.042 | 0.246* | -0.118 | -0.091 | **0.636**** | 0.065 | 1 | | | | | | |
| Pb | -0.022 | -0.071 | -0.134 | 0.086 | -0.032 | 0.006 | -0.153 | -0.038 | -0.011 | -0.038 | 0.069 | -0.091 | -0.038 | 1 | | | | | |
| Cu | -0.024 | -0.014 | 0.003 | -0.006 | -0.003 | -0.048 | -0.169 | -0.083 | 0.058 | -0.063 | -0.035 | -0.084 | -0.057 | 0.016 | 1 | | | | |
| Zn | -0.069 | 0.071 | -.399** | 0.091 | 0.035 | 0.049 | -0.030 | 0.062 | -0.064 | -0.06 | 0.203 | 0.199 | 0.011 | 0.096 | 0.490** | 1 | | | |
| Cd | 0 | -0.083 | -0.171 | 0.116 | -0.063 | 0.019 | -0.109 | 0.005 | 0.005 | -0.093 | 0.123 | -0.097 | -0.053 | **0.953**** | 0.086 | 0.19 | 1 | | |
| Hg | -0.105 | 0.175 | 0.126 | 0.057 | 0.054 | 0.078 | -0.169 | 0.096 | 0.102 | 0.026 | 0.072 | -0.087 | 0.092 | -0.143 | 0.227* | -0.206 | -0.174 | 1 | |
| Coliform | -0.049 | -0.046 | 0.101 | 0.237* | 0.156 | 0.085 | -0.185 | -0.006 | 0.381** | 0.067 | -0.047 | -0.056 | -0.079 | 0.01 | 0.290* | -0.037 | 0.025 | 0.160 | 1 |
| *E.coli* | -0.005 | -0.066 | 0.113 | -0.063 | -0.076 | -0.092 | -0.023 | -0.054 | 0.247* | 0.117 | -0.063 | -0.088 | -0.068 | 0.243* | 0.051 | -0.085 | 0.243* | -0.006 | 0.389** |

**Note:** *Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed).

WPI classification, groundwater quality at sampling points was classified as very good, good, slightly polluted, and highly polluted, with the proportion of wells being 68.4, 7.9, 13.2, and 10.5% in the dry season and 57.9, 18.4, 2.6 and 21.1% in the rainy season. The average WPI of the aquifers ranged from 0.29±0.09 in the Miocene n13 aquifer to 0.83±0.72 in the Holocene qh aquifer ($p < 0.05$). The average WPI of the Pleistocene aquifers was higher than that of the Pliocene and Miocene aquifers in the dry season ($p < 0.05$; Figure). The upper Pliocene (n22), upper Pliocene (n21), and upper Miocene (n13) aquifers all had excellent water quality, while the upper aquifers of Holocene qh and Pleistocene qp3 had good water quality, and the remaining two aquifers have average water quality. 100% of the water samples of the upper Pliocene (n21) and upper Miocene (n13) aquifers have excellent and good water quality (Figure 2).

## GWQI index

GWQI fluctuated from 21.75±7.45 (GW5) to 137.27±75.00 (GW7) with an average of 64.67±41.85 in the dry season, and in the rainy season, it ranged from 14.53±7.82 (GW14) to 182.39±90.17 (GW4) with an average of 68.37±51.88. There was no difference between the average GWQI between the dry and rainy seasons at all sampling points ($p > 0.05$). There was a change between monitoring points in dry and rainy seasons ($p < 0.05$). Classification of water quality according to GWQI showed that groundwater quality at sampling points was excellent, good, bad, terrible, and unsuitable for use, with

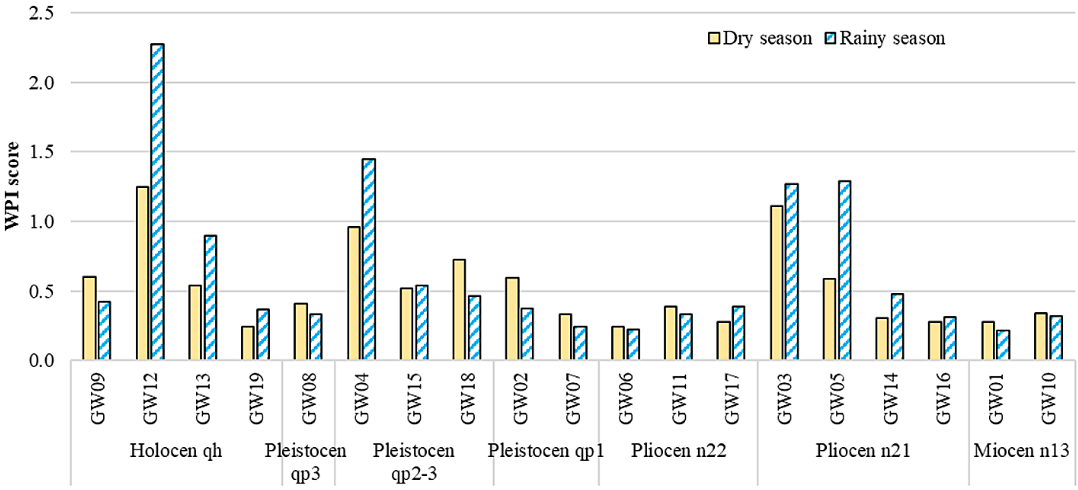


**Figure 2.** Seasonal variation of groundwater WPI

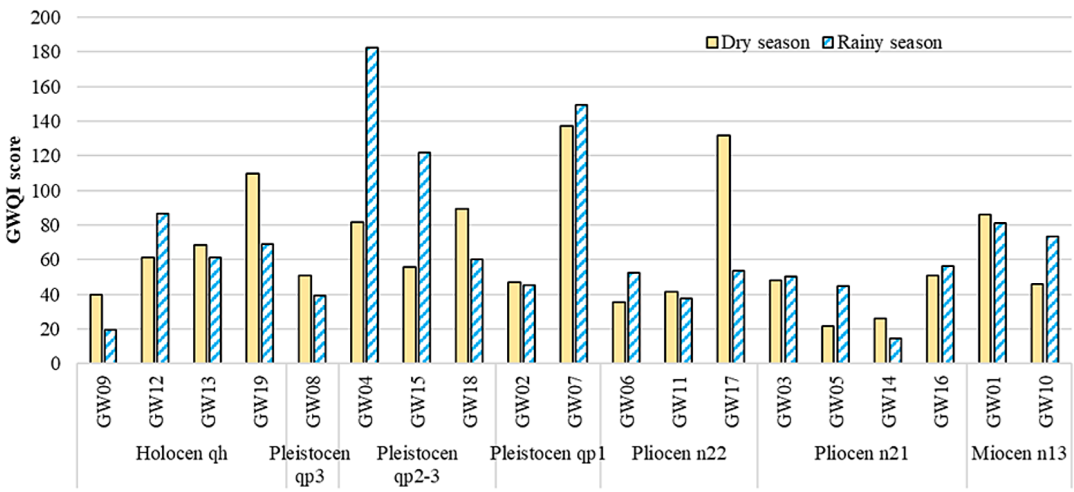


**Figure 3.** Seasonal variation of groundwater WQI

sample rates of 10.5, 34.2, 26.3, 15.8 and 13.2% in the dry season and 26.3, 15.8, 26.3, 13.2 and 18.4% in the rainy season, respectively. The average GWQI values between aquifers also differed; the lowest was the Pliocene 21 aquifer (39.09), and the highest was the Pleistocene qp1 aquifer (94.70) ($p < 0.05$). According to the GWQI results, the Pliocene n21 aquifer had good water quality, the Pliocene n22, Holocene qh, and Miocene n13 aquifers had terrible water quality, and the remaining two aquifers had terrible water quality (Figure 3).

## CA analysis

The CA analysis results of WPI classified the monitoring wells into five groups. Group 1 had excellent water quality with wells 1, 6, 7, 8, 10, 11, 14, 16, 17, 19. Group 2 has good water quality with wells 2, 9, 15, 18. Group 3 had average water quality with wells 5, 13. Group 4 had highly polluted water quality with two wells 3, 4. Group 5 had well 12 with highly polluted water quality but higher WPI than group 4. The results of the factor variance analysis showed that the water quality parameters affecting the water quality are pH, TH, TS, $Cl^-$, $SO_4^{2-}$, $NO_2^-$, Mn, Fe, and As.

The CA analysis results based on GWQI also classified the monitoring wells into five groups. Group 1 had good water quality with wells 5, 9 and 14. Group 2, with wells 2, 3, 6, 11, 16 and 8 also had good water quality, but the GWQI index was twice as high as group 1. Group 3 had poor water quality with wells 13, 10, 12, 18. Group 4 had inferior water quality with wells 1, 17, 15, 19. Group 5, with wells 4 and 7 had water quality unsuitable for drinking, with the main influencing parameters being TH, TS, turbidity, $Cl^-$, $SO_4^{2-}$ and Fe (Figure 4, Table 6).

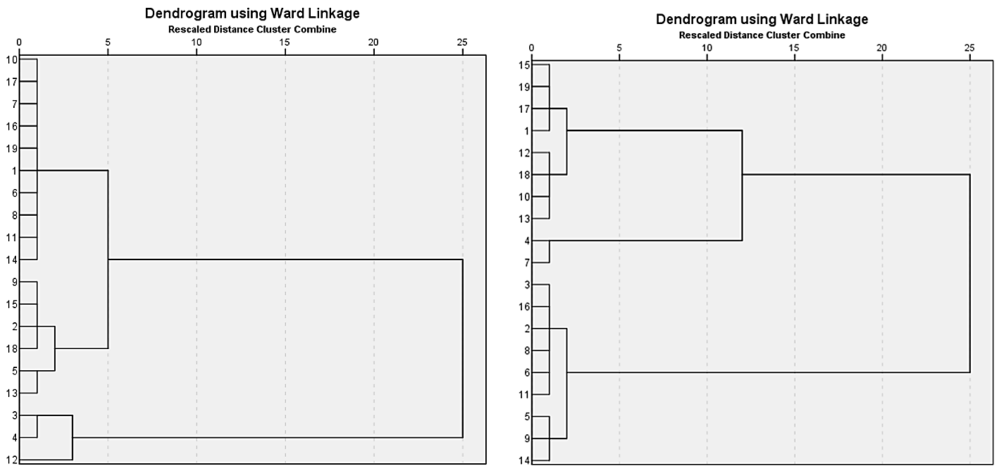


**Figure 4.** Clustering well locations based on WPI (left) and GWQI (right)

**Table 6.** CA analysis results and water quality of wells in groups

| CA-WPI | Well | Water quality | WPI score (Mean±std) | CA-GWQI | Well | GWQI score (Mean±std) | Water quality |
|---|---|---|---|---|---|---|---|
| 1 | GW1, GW6, GW7, GW8, GW10, GW11, GW14, GW16, GW17, GW19 | Excellent | 0.32±0.05 | 1 | GW5, GW14, GW9 | 27.77±6.79 | Good |
| 2 | GW2, GW9, GW15, GW18 | Good | 0.53±0.05 | 2 | GW2, GW6, GW11, GW3, GW16, GW8 | 46.28±4.73 | Good |
| 3 | GW5, GW13 | Moderate | 0.83±0.16 | 3 | GW12, GW13, GW1, GW10, GW15, GW18 | 68.26±7.32 | Poor |
| 4 | GW3, GW4 | High pollution | 1.2±0.01 | 4 | GW17, GW19 | 88.65±3.75 | Very poor |
| 5 | GW12 | High pollution | 1.76 | 5 | GW4, GW7 | 137.67±7.83 | Not suitable for drinking water |

## Potential sources of groundwater variations

The total variance of groundwater quality variation. It can be seen that the first PC set the most critical environmental variables with a high correlation coefficient with PC. The subsequent PCs explain other important environment variables not shown in the previous PC. According to Elemile et al. (2021), the correlation between environmental quality variables and the main component is based on factor load. It is divided into three levels, namely strong (0.75), medium (0.75–0.5), and weak (0.5–0.3). From there, it helps to identify pollution sources in the study area that can change groundwater quality.

PCA analysis in this study was based on the monitoring results of 20 water quality parameters: temperature, pH, TH, Turb., TSS, $SO_4^{2-}$, $Cl^-$, F, N-$NO_3^+$, N-$NO_2^-$, Mn, As, Fe, Pb, Cu, Zn, Cd, Hg, Coliform and *E. Coli* of 19 wells with four sampling periods. Seven main groups with eigenvalues greater than 1 identified and explained 73.09% of water quality. The observed variances for the groups PC1, PC2, PC3, PC4, PC5, PC6 and PC7 were 22.06, 11.88, 11.11, 8.63, 7.89, 6.16 and 5.37%, respectively (Figure 5).

PC1 was the group of most important environmental parameters with the highest coefficient of influence on groundwater quality (22.06%) of Fe, Mn (weak), TS (medium), $SO_4^{2-}$, Cl- and TH (strong) variables with factor loadings of 0.422, 0.430, 0.670, 0.800, 0.913 and 0.935, respectively, while pH had a moderate negative correlation (-0.586) with PC1. The variables in PC1 mainly originated from chemical processes and waste from agriculture, industry, and daily life [36, 52]. PC2 had a strong correlation with Mn (0.703), Turb. (0.842) and As (0.881), and a weak correlation with Temp. (0.352) and $SO_4^{2-}$ (0.354). Mn and As sources were also mainly natural due to the interaction between water and rock. PC3 strongly correlated positively with Pb (0.953) and Cd (0.956). PC4 had a positive correlation with N-$NO_2^-$ (0.696) and N-$NO_3^-$ (0.808) but a negative correlation with F (-0.547). PC4 was a group of factors related to nutritional factors and impacts from fertilizers and waste in agricultural production and industrial and domestic waste. PC5 positively correlated with Cu (0.812) and Zn (0.863), a group of heavy metal factors. PC6 positively correlated with Coliform (0.758) and E. coli (0.823), originating mainly from human and animal waste and organic fertilizers. PC7 had a positive correlation with temperature (0.418), F (0.337), and Fe (0.448) but a negative correlation with Hg (-0.748). The PCA results showed that the 20 observed groundwater quality parameters significantly impacted the change in groundwater quality in 19 monitoring wells (Table 7). It has also been noted that the source of groundwater pollution in Dong Thap province in 2024 may originate from natural sources such as weathering, interactions between water and rock, and anthropogenic sources such as waste from domestic activities, agricultural production, and industrial wastewater. From the above reality, it was necessary to find solutions to

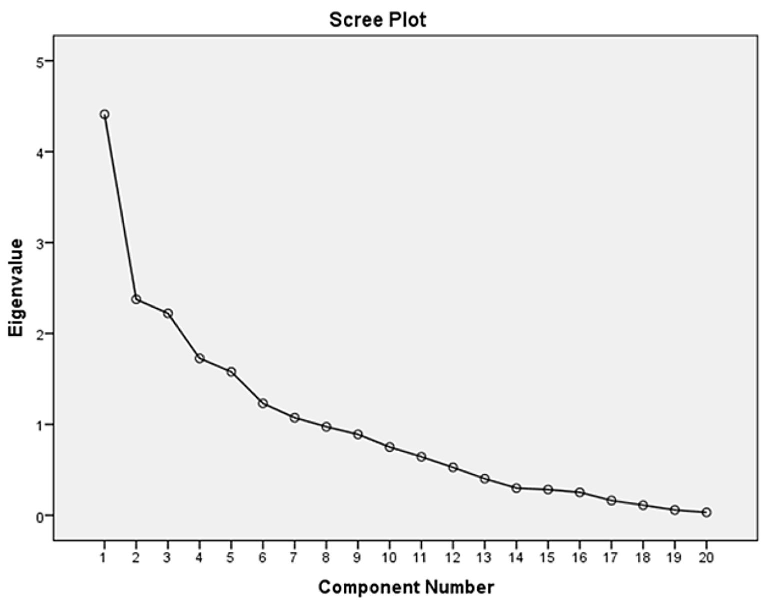


**Figure 5.** Scree plot of PCA

**Table 7.** PCA analysis of water quality parameters concentration

| Par/PC | PC1 | PC2 | PC3 | PC4 | PC5 | PC6 | PC7 |
|---|---|---|---|---|---|---|---|
| Temp. | -0.001 | 0.352 | -0.032 | 0.371 | -0.077 | -0.055 | **0.418** |
| pH | **-0.586** | -0.192 | -0.212 | 0.35 | -0.285 | 0.191 | -0.138 |
| TH | **0.935** | 0.002 | 0.076 | -0.068 | 0.042 | 0.092 | 0.011 |
| TDS | **0.67** | 0.027 | -0.055 | -0.003 | -0.027 | 0.003 | -0.147 |
| Turb. | 0.211 | **0.842** | -0.13 | -0.056 | 0.06 | 0.036 | 0.062 |
| $Cl^-$ | **0.913** | 0.17 | -0.022 | 0.169 | -0.033 | 0.013 | 0.062 |
| F | 0.059 | -0.017 | -0.202 | **-0.547** | -0.243 | 0.082 | **0.337** |
| $SO_4^{2-}$ | **0.8** | 0.354 | -0.013 | -0.052 | -0.06 | -0.024 | 0.081 |
| $N\text{-}NO_3^-$ | -0.105 | -0.036 | -0.097 | **0.808** | -0.084 | 0.058 | 0.161 |
| $N\text{-}NO_2^-$ | 0.139 | -0.189 | -0.013 | **0.696** | -0.016 | 0.349 | -0.17 |
| Mn | 0.43 | **0.703** | 0.183 | -0.064 | 0.064 | -0.112 | -0.121 |
| As | 0.039 | **0.881** | -0.014 | -0.063 | -0.041 | -0.041 | -0.079 |
| Fe | 0.422 | 0.087 | -0.241 | -0.297 | 0.15 | 0.076 | **0.448** |
| Pb | 0.009 | -0.02 | **0.953** | 0.003 | 0.008 | 0.083 | 0.04 |
| Cu | -0.077 | -0.014 | -0.025 | 0.043 | **0.812** | 0.199 | -0.261 |
| Zn | 0.091 | 0.038 | 0.119 | -0.056 | **0.863** | -0.121 | 0.25 |
| Cd | 0.027 | -0.017 | **0.956** | -0.021 | 0.093 | 0.096 | 0.07 |
| Hg | 0.062 | 0.175 | -0.206 | 0.051 | -0.008 | 0.112 | **-0.748** |
| Coliform | 0.158 | -0.101 | -0.047 | 0.159 | 0.174 | **0.758** | -0.248 |
| *E.coli* | -0.128 | 0.027 | 0.245 | 0.042 | -0.088 | **0.823** | 0.108 |
| Eigenvalues | 4.41 | 2.38 | 2.22 | 1.73 | 1.58 | 1.23 | 1.07 |
| %Var. | 22.06 | 11.88 | 11.11 | 8.63 | 7.89 | 6.16 | 5.37 |
| Cum.%Var. | 22.06 | 33.94 | 45.04 | 53.67 | 61.57 | 67.72 | 73.09 |

limit the occurrence and impact of anthropogenic pollution sources and minimize groundwater pollution in the study area in the future.

The WPI analysis results showed that the water quality was mainly classified as very good, good, slightly polluted, and highly polluted, with the proportion of wells being 68.4, 7.9, 13.2, and 10.5% in the dry season and 57.9, 18.4, 2.6 and 21.1% in the rainy season. Classification of water quality according to GWQI showed that groundwater quality at sampling points was excellent, good, bad, terrible, and unsuitable for use, with sample rates of 10.5, 34.2, 26.3, 15.8 and 13.2% in the dry season and 26.3, 15.8, 26.3, 13.2 and 18.4% in the rainy season, respectively. The water quality in the dry season was not much different from the rainy season. However, the water quality in the deep aquifers was always better than in the shallow aquifers. The CA analysis results showed that the average water quality of 19 monitoring wells is divided into five groups according to WPI and GWQI. However, there was also a discrepancy between these two indices. The PCA analysis results of 20 parameters showed that 7 PC groups explain 73.09% of groundwater quality. The source of groundwater pollution in the locality was mainly natural, such as weathering the interaction between water and rock, and on the other hand, it is artificial, such as waste from domestic activities, agricultural production and industrial wastewater.

## CONCLUSIONS

The quality of groundwater at 19 monitoring wells in Dong Thap province in 2024 was quite good, and most of them met the regulations of QCVN and WHO, except for the parameters TH, TDS, Cl-, Mn, Fe in shallow wells, and coliform and E.coli which were much higher than the standards. Water quality had less variation between sampling months than well depths. Water quality in deep aquifers such as Miocene n13, Pliocene n21, and Pliocene n22 was often better than in shallow aquifers with turbidity and TH, TDS, $Cl^-$, $SO_4^{2-}$, and Fe concentration in deep wells lower than shallow aquifers. The parameters had a moderate to strong correlation, such as the negative correlation of pH with TH, strong anions $SO_4^{2-}$, $Cl^-$, and metals that often form complexes with these anions Mn, Fe, and Zn. In addition, there was a correlation between strong anions and heavy metals in water, between coliform and *E.coli.*

The WPI analysis results showed that the water quality is mainly in the good, good group at 76.3% and in the excellent, good group according to the GWQI value. The water quality in the dry season was relatively better than in the rainy season, and the water in the deep aquifer was always better than the shallow aquifer.

The CA analysis results showed that the average water quality of 19 monitored wells is divided into five groups according to WPI and GWQI. Still, there was also a discrepancy between these two indices. The PCA analysis results of 20 parameters showed that 7 PC groups explain 73.09% of groundwater quality and the source of groundwater pollution in the locality was mainly natural, such as weathering, the interaction between water and rock, and on the other hand, it was artificial such as waste from domestic activities, agricultural production and industrial wastewater.

## Acknowledgements

The authors would like to express our sincere attitude toward the Department of Natural Resources and Environment of Dong Thap province for data provision. The scientific and personal views presented in this paper do not necessarily reflect the views of the data provider.

## REFERENCES

1. Abbasnia, A., Yousefi, N., Mahvi, A. H., Nabizadeh, R., Radfard, M., Yousefi, M., & Alimohammadi, M. (2018). Evaluation of groundwater quality using water quality index and its suitability for assessing water for drinking and irrigation purposes: Case study of Sistan and Baluchistan province (Iran). *Human and Ecological Risk Assessment: An International Journal, 25*(4), 988–1005. https://doi.org/10.1080/10807039.2018.1458596
2. Adimalla N. & Qian H. (2019). Hydrogeochemistry and fluoride contamination in the hard rock terrain of central Telangana, India: analyses of its spatial distribution and health risk. *Applied Sciences,* 1:202. https://doi.org/10.1007/s42452-019-0219-8
3. Ahmed A.K.A., El-Rawy M. (2024). The impact of aquifer recharge on groundwater quality, in: managed aquifer recharge in MENA countries: Developments, Applications, Challenges, Strategies, and Sustainability, 207–222. Earth and Environmental Sciences Library. Springer, Cham. https://doi.org/10.1007/978-3-031-58764-1_10
4. Al-Ridah Z. A., Naje A. S., Hassan D. F and Al-Zubaid H. A. M. (2021). Environmental assessment of groundwater quality for irrigation purposes: A case study of Hillah City In Iraq. *Pertanika J. Sci. & Technol, 29*(3), 1579–1593. https://doi.org/10.47836/pjst.29.3.10
5. Biswas, P., Hossain, M., & Patra, P. K. (2023). Arsenic hydrogeochemistry, quality assessment, and associated health risks of groundwater through the novel water pollution index (WPI) and GIS approach. *Groundwater for Sustainable Development*, *21*, 100944. https://doi.org/10.1016/j.gsd.2023.100944
6. Chakraborty, B., Roy, S., Bera, A., Adhikary, P. P., Bera, B., Sengupta, D., Bhunia, G. S., & Shit, P. K. (2021). Geospatial assessment of groundwater quality for drinking through water quality index and human health risk index in an upland area of Chota Nagpur Plateau of West Bengal, India. *Spatial Modeling and Assessment of Environmental Contaminants, Springer, Cham, Switzerland*. https://doi.org/10.1007/978-3-030-63422-3_19
7. Das, T. K., Shaibur, M. R., & Rahman, M. M. (2021). Groundwater chemistry at deep aquifer in Koyra: Khulna, Bangladesh. *Current World Environment, 16*(2), 460–471. https://doi.org/10.12944/cwe.16.2.12
8. Dash, S., Kalamdhad, A.S. (2021). Hydrochemical dynamics of water quality for irrigation use and introducing a new water quality index incorporating multivariate statistics. *Environ Earth Sci, 80*, 73. https://doi.org/10.1007/s12665-020-09360-1
9. DONRE. 2013. Report explaining the Planning for management, exploitation and protection of groundwater resources in Dong Thap province until 2015, with orientation to 2020. Department of Natural Resources and Environment of Dong Thap. Ly Tu Trong, Co Lanh city, Dong Thap province, Vietnam (Vietnamese).
10. DONRE. 2025. Environmental monitoring report. Department of Natural Resources and Environment of Dong Thap province (DONRE). Ly Tu Trong, Co Lanh city, Dong Thap province, Vietnam (Vietnamese).
11. Elemile, O. O., Ibitogbe, E. M., Folorunso, O. P., Ejiboye, P. O., & Adewumi, J. R. (2021). Principal component analysis of groundwater sources pollution in Omu-Aran Community, Nigeria. *Environmental Earth Sciences, 80*(20), 690. https://doi.org/10.1007/s12665-021-09975-y
12. Farooqi, A., Masuda, H., Kusakabe, M., Naseem, M., & Firdous, N. (2007). Distribution of highly

arsenic and fluoride contaminated groundwater from east Punjab, Pakistan, and the controlling role of anthropogenic pollutants in the natural hydrological cycle. *Geochemical Journal, 41*(4), 213–234. https://doi.org/10.2343/geochemj.41.213

13. Feher, I.C., Zaharie, M., Oprean, I. (2016). Spatial and seasonal variation of organic pollutants in surface water using multivariate statistical techniques. *Water Sci. Technol.*, *74*, 1726–1735.
14. Ghosh, G. C., Khan, Md. J. H., Chakraborty, T. K., Zaman, S., Kabir, A. H. M. E., & Tanaka, H. (2020). Human health risk assessment of elevated and variable iron and manganese intake with arsenic-safe groundwater in Jamshoro, Bangladesh. *Scientific Reports, 10*(1), 1–9. https://doi.org/10.1038/s41598-020-62187-5
15. Giao N. T., Nhien H.T.H. 2023. Characterization of groundwater quality and human health risk assessment. *Civil Engineering Journal. 9*(3), 618–628. http://dx.doi.org/10.28991/CEJ-2023-09-03-09
16. Giao, N. T., Anh, P. K., & Nhien, H. T. H. (2022b). Groundwater quality assessment using groundwater quality index and multivariate statistical methods and human health risk assessment in a coastal region of the Vietnamese Mekong Delta. *Applied Environmental Research, 44*(2), 68–85. https://doi.org/10.35762/AER.2022.44.2.6
17. Giao, N. T., Nhien, H. T. H., & Anh, P. K. (2022a). Groundwater quality assessment using classification and multi-criteria methods: A case study of Can Tho City, Vietnam. *Environment and Natural Resources Journal, 20*(2), 179–191. https://doi.org/10.32526/ennrj/20/202100183
18. Heale, R., Twycross, A. (2015). Validity and reliability in quantitative studies. *Evid. Based Nurs. 18*, 66–67. https://doi.org/10.1136/eb-2015-102129
19. Hossain, M., & Patra, P. K. (2020). Water pollution index—a new integrated approach to rank water quality. *Ecological Indicators, 117*, 106668. https://doi.org/10.1016/j.ecolind.2020.106668
20. Kieu, L.D. & Nguyen P.Q. 2024. Groundwater quality assessment in the middle-upper Pleistocene aquifer. *Civil Engineering Journal, 10*(7), 2357–2369, http://dx.doi.org/10.28991/CEJ-2024-010-07-018
21. Kubier, A., Hamer, K., & Pichler, T. (2020). Cadmium background levels in groundwater in an area dominated by agriculture. *Integrated Environmental Assessment and Management, 16*(1), 103–113. https://doi.org/10.1002/ieam.4198
22. Kumar P. R, S. Gowd S, Krupavathi C. (2024). Groundwater quality evaluation using water quality index and geospatial techniques in parts of Anantapur District, Andhra Pradesh, South India. *Hydro Research, 7*, 86-98. https://doi.org/10.1016/j.hydres.2024.01.001
23. Mairizki, F., & Cahyaningsih, C. (2016). Ground water quality analysis in the coastal of Bengkalis City using geochemistry approach. *Journal of Dynamics (International Journal of Dynamics in Engineering and Sciences), 1*(2), 82-87. https://doi.org/10.22216/JoD.2016.V1.82-87
24. Minh, H. V. T., Avtar, R., Kumar, P., Tran, D. Q., Van Ty, T., Behera, H. C., & Kurasaki, M. (2019). Groundwater quality assessment using fuzzy-AHP in An Giang Province of Vietnam. *Geosciences (Switzerland), 9*(8), 330. https://doi.org/10.3390/geosciences9080330
25. Nadiri, A. A., Barzegar, R., Sadeghfam, S., & Rostami, A. A. (2022). Developing a data-fused water quality index based on artificial intelligence models to mitigate conflicts between GQI and GWQI. *Water (Switzerland), 14*(19), 3185. https://doi.org/10.3390/w14193185
26. Nguyen, A. H., Nguyen, M. P. L., Pham, N. T. T., Tat, V. M. H., Luu, L. K., & Vo, P. L. (2021). Health risk assessment of groundwater consumption for drinking and domestic purposes in Xuyen Moc District, Ba Ria - Vung Tau Province, Vietnam. *IOP Conference Series: Earth and Environmental Science, 652*(1), 12018. https://doi.org/10.1088/1755-1315/652/1/012018
27. Omer, N.H., 2019. Water quality parameters. *Water quality-science, assessments and policy, 18*, 1–34. https://doi.org/10.5772/intechopen.89657
28. Ouhakki, H., Hmouni, D., Fallah K.E., Mejdoub, N.E., Adiba, A. (2025). Groundwater quality dynamics in Doukkala, Morocco - Exploring seasonal and temporal variations in physicochemical and bacteriological traits. *Journal of Ecological Engineering, 26*(1), 95–108. https://doi.org/10.12911/22998993/195357
29. Paternoster, M., Buccione, R., Canora, F., Buttitta, D., Panebianco, S., Rizzo, G., Sinisi, R., Summa, V., & Mongelli, G. (2021). Hydrogeochemistry and groundwater quality assessment in the High Agri Valley (Southern Italy). *Geofluids*, 1–15. https://doi.org/10.1155/2021/6664164
30. People's Committee of Dong Thap province. 2024. Official dispatch 361/UBND-DTQH dated October 9, 2024; information and data requested to be provided to prepare a thematic report on the current status of the urban environment, current situation, and solutions (Vietnamese).
31. Prathumratana, L., Sthiannopkao, S., Kim, K.W. (2008). The relationship of climatic and hydrological parameters to surface water quality in the lower Mekong River. *Environ. Int. 34*, 860–866. https://doi.org/10.1016/j.envint.2007.10.011
32. Ram, A., Tiwari, S. K., Pandey, H. K., Chaurasia, A. K., Singh, S., & Singh, Y. V. (2021). Groundwater quality assessment using water quality index (WQI) under GIS framework. *Applied Water Science, 11*(2),

1–20. https://doi.org/10.1007/s13201-021-01376- 7

33. Ramesh, K., & Thirumangai, V. (2014). Impacts of tanneries on quality of groundwater in Pallavaram, Chennai Metropolitan City. *International Journal of Engineering Research and Applications, 4*(1), 63–70.
34. Scanlon B.R., Fakhreddine S., Rateb A., de Graaf I., Famiglietti J., Gleeson T., Grafton R.Q., Jobbagy E., Kebede S., Kolusu S.R. (2023). Global water resources and the role of groundwater in a resilient water future. *Nature Reviews Earth & Environment 4*, 87–101
35. Sharma, M. K., & Kumar, M. (2020). Sulphate contamination in groundwater and its remediation: an overview. *Environmental Monitoring and Assessment, 192*(2), 1–10. https://doi.org/10.1007/s10661-019-8051-6
36. Sunitha V., Muralidhara Reddy B. (2018). Defluoridation of water using menthe longifolia (Mint) as Bioadsorbent. *J Geophy Union 22*(2), 207–211.
37. Sunitha V, Muralidhara Reddy B, Ramakrishna Reddy M (2012) Groundwater contamination from agro-chemicals in irrigated environment: field trials. Int J Adv AppSci Res 3(5), 3382–3386.
38. Sunitha V, Reddy YS (2019) Hydrogeochemical evalution of groundwater in and around Lakkireddipalli and Ramapuram, YSR District, Andhra Pradesh India. *Hydro Res 2*, 85–96. https://doi.org/10.1016/j.hydres.2019.11.008
39. Sunitha, V., & Reddy, B. M. (2022). Geochemical characterization, deciphering groundwater quality using pollution index of groundwater (PIG), water quality index (WQI) and geographical information system (GIS) in hard rock aquifer, South India. *Applied Water Science, 12*(3), 41. https://doi.org/10.1007/s13201-021-01527-w
40. TCVN 6663-11:2011 (ISO 5667-11:2009). (2011). National standard on Water quality - Sampling - Part 11: Guidance on sampling of groundwaters. Ministry of Science and Technology, Hanoi, Vietnam. Available online: https://thuvienphapluat.vn/TCVN/Tai-nguyen-Moi-truong/TCVN-6663-11-2011-Chat-luong-nuoc-Lay-mau-Huong-dan-lay-mau-nuoc-ngam-905298.aspx (accessed on June 2025). (In Vietnamese).
41. Tham, T. T., Thi Hien, D., Thuy Chung, N., & Tra Mai, N. (2022). Assessment of groundwater quality in the Holocene aquifer in Duy Tien District, Ha Nam Province using groundwater quality index (GWQI). *VNU Journal of Science: Earth and Environmental Sciences, 38*(1). https://doi.org/10.25073/2588-1094/vnuees.4781
42. Tran, D. A., Tsujimura, M., Loc, H. H., Dang, D. H., Le Vo, P., Thu Ha, D., Thu Trang, N. T., Chinh, L. C., Bich Thuc, P. T., Dang, T. D., Batdelger, O., & V. Nguyen, T. (2021). Groundwater quality evaluation and health risk assessment in coastal lowland areas of the Mekong Delta, Vietnam. *Groundwater for Sustainable Development, 15*,100679. https://doi.org/10.1016/j.gsd.2021.100679
43. Vietnamese Ministry of Natural Resources and Environment (MONRE). 2023. National technical regulation on Groundwater quality (QCVN08-MT:2015/BTNMT). Ministry of Natural Resources and Environment, Hanoi, Vietnam.
44. World Health Organization (WHO). 2022. Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. Geneva: Licence: CC BY-NC-SA 3.0 IGO.
45. Xia, X., Teng, Y., & Zhai, Y. (2022). Biogeochemistry of Iron Enrichment in Groundwater: An Indicator of Environmental Pollution and Its Management. *Sustainability (Switzerland), 14*(12), 7059. https://doi.org/10.3390/su14127059
46. Ye, Q., Park, J. E., Gugnani, K., Betharia, S., Pino-Figueroa, A., & Kim, J. (2017). Influence of iron metabolism on manganese transport and toxicity. *Metallomics, 9*(8), 1028-1046. https://doi.org/10.1039/c7mt00079k
47. You X., Liu S., Dai C., Guo Y., Zhong G., Duan Y. (2020). Contaminant occurrence and migration between high-and low-permeability zones in groundwater systems: A review. *Science of the total environment, 743*, 140703. https://doi.org/10.1016/j.scitotenv.2020.140703
48. Zhou, F., Liu, Y., Guo, H. (2007). Application of multivariate statistical methods to water quality assessment of the water courses in north western new territories Hong Kong. *Environ. Monit. Assess. 132,*1–13. https://doi.org/10.1007/s10661-006-9497-x